

INTERMEDIATE-MASS BLACK HOLES IN EARLY GLOBULAR CLUSTERS

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ABSTRACT

Spectroscopic and photometric observations show that many globular clusters host multiple stellar populations, challenging the common paradigm that globular clusters are “simple stellar populations” composed of stars of uniform age and chemical composition. The chemical abundances of second-generation (SG) stars constrain the sources of gas out of which these stars must have formed, indicating that the gas must contain matter processed through the high-temperature CNO cycle. First-generation massive Asymptotic Giant Branch (AGB) stars have been proposed as the source of this gas. In a previous study, by means of hydrodynamical and N-body simulations, we have shown that the AGB ejecta collect in a cooling flow in the cluster core, where the gas reaches high densities, ultimately forming a centrally concentrated subsystem of SG stars. In this Letter we show that the high gas density can also lead to significant accretion onto a pre-existing seed black hole. We show that gas accretion can increase the black hole mass by up to a factor of 100. The details of the gas dynamics are important in determining the actual black hole growth. Assuming a near-universal seed black hole mass and small cluster-to-cluster variations in the duration of the SG formation phase, the outcome of our scenario is one in which the present intermediate-mass black hole (IMBH) mass may have only a weak dependence on the current cluster properties. The scenario presented provides a natural mechanism for the formation of an IMBH at the cluster center during the SG star-formation phase.

Subject headings: globular clusters: general

1. INTRODUCTION

If globular clusters follow the same “ $M_{BH} - \sigma$ ” relation between central black hole mass and effective velocity dispersion as is observed in galaxies (Tremaine et al. 2002), many clusters should host intermediate-mass black holes (IMBHs) with masses in the range $10^2 \lesssim M_{BH}/M_{\odot} \lesssim 10^4$. Unfortunately, hard observational evidence for IMBHs in globular clusters has proved elusive. Currently the strongest case is the massive cluster G1 in M31, where dynamical, X-ray, and radio studies are consistent with a mass $M_{BH} \sim 2 \times 10^4$ (Gebhardt et al. 2005, Ulvestad et al. 2007). In our own Galaxy, a measurement of an IMBH mass $M_{BH} \sim 4 \times 10^4 M_{\odot}$ has been reported for ω Centauri (Noyola et al. 2008), although this result has been questioned in a recent study (Anderson & van der Marel 2010, van der Marel & Anderson 2010) suggesting that the IMBH signature becomes much weaker when a more accurate estimate of the cluster center is used. Recently Ibata et al. (2009) have reported evidence of a density and kinematic cusp in the core of M54, a cluster located at the center of the Sagittarius dwarf galaxy; their models suggest that the cusp could be due to a $\sim 10^4 M_{\odot}$ IMBH.

For most Galactic globular clusters, kinematic and structural data currently provide only upper limits on possible IMBH masses (McLaughlin et al. 2006, Pasquato et al. 2009, van der Marel & Anderson 2009).

However, these upper limits are larger than the values of M_{BH} expected from the $M_{BH} - \sigma$ relation, and do not exclude the possibility that many globular clusters host IMBHs with masses in the above range (van der Marel & Anderson 2009).

The presence of an IMBH in a globular cluster has important consequences for the cluster’s structure, kinematics, internal energetics and long-term dynamical evolution (see e.g. Baumgardt et al. 2004, Heggie et al. 2007, Trenti et al. 2007, Miocchi 2007; see also McMillan 2008 for a review). In addition, Eddington accretion onto IMBHs has been proposed as the mechanism powering some ultraluminous X-ray sources (e.g. Farrell et al. 2009), and IMBHs have long been recognized as potential rich sources of gravitational waves detectable by LISA (Miller 2009). For these reasons, despite the lack of strong observational constraints, the formation and consequent properties of IMBHs have become a topic of considerable theoretical and observational interest.

One possible IMBH formation mechanism is direct collapse of a very massive ($\geq 250 M_{\odot}$) Population III star (see e.g. Bond et al. 1984, Madau & Rees 2001 and references therein; but see Abel et al. 2002 for hydrodynamical simulations suggesting that these stars would form in isolation). For non-primordial or more massive IMBHs, the leading formation mechanisms center on dynamical processes in dense star clusters. These include runaway mergers of massive stars in clusters with high central den-

sities (Portegies Zwart & McMillan 2002, Gürkan et al. 2004, Portegies Zwart et al. 2004), and merging of black holes in binaries (see O'Leary et al. 2006 and references therein). However, numerous potential problems affecting these models have been pointed out in the recent literature, suggesting that the net growth rate and hence the final mass of the resulting IMBH may be much lower than suggested by earlier dynamical simulations (Yungelson et al. 2008, Glebbeek et al. 2009).

Thus, while there appear to be numerous plausible stellar, binary, and dynamical pathways to the formation of relatively “low-mass” ($\sim 100 - 200 M_{\odot}$) IMBHs in clusters, there is currently no clear consensus on a mechanism for the production of high-mass ($10^3 - 10^4 M_{\odot}$) IMBHs.

In this Letter we propose a new scenario for the growth of IMBHs in early globular clusters. It is a natural consequence of the physical conditions that may have obtained in cluster cores during the formation of the second generation (hereafter SG) stars now observed in many globular clusters. Specifically, we show that accretion by a pre-existing seed black hole of just a small fraction of the gas from which the SG stars formed can lead to black holes in the high-mass ($10^3 - 10^4 M_{\odot}$) IMBH range.

The structure of this Letter is as follows. In Section 2 we briefly review the observational evidence for multiple stellar populations in globular clusters, and summarize the main elements of our model for the formation and evolution of multiple populations. In Section 3, we present our scenario for IMBH growth. We discuss some consequences of this scenario in Section 4.

2. MULTIPLE STELLAR POPULATIONS IN GLOBULAR CLUSTERS

Spectroscopic and photometric observations provide strong evidence for multiple stellar generations in globular clusters.

Spectroscopic studies have shown that, even in clusters whose stars have a common Fe abundance, there are substantial star-to-star differences in the abundances of lighter elements (see Gratton et al. 2004 and references therein, and Carretta et al. 2009a,b for a recent spectroscopic study of 19 Galactic clusters). All the Galactic globular clusters for which spectroscopic studies have been carried out show evidence of multiple stellar populations, and in all cases SG stars make up a significant fraction (50–80%) of the total (D'Antona & Caloi 2008, Carretta et al. 2009a,b).

Several recent photometric studies have provided further support for these results by showing the photometric fingerprints of multiple populations (multiple main sequences, significant main sequence broadening, or sub-giant branch splits) in the color-magnitude diagrams both of “normal” clusters in the Galaxy (Piotto et al. 2007, Marino et al. 2008, Milone et al. 2008, Anderson et al. 2009), and of more complex systems such as ω Cen (Lee et al. 1999, Pancino et al. 2000, Bedin et al. 2004, Villanova et al. 2007), M22 (Marino et al. 2009, Lee et al. 2009) and probably Terzan 5 (Ferraro et al. 2009).

The differences in light-element abundances suggest that SG stars formed out of gas containing matter processed through high-temperature CNO cycle reactions in first-generation (FG) stars. The main candidates currently suggested as possible sources of gas for SG formation are massive AGB stars (Ventura et al. 2001) and

rapidly rotating massive stars (Decressin et al. 2007). Although many aspects of these two scenarios are still under investigation, in order to form the large mass of SG stars suggested by observations, both scenarios require that either the IMF of the FG stars was highly anomalous, with an unusually large fraction of massive stars, or the FG population had a normal IMF but was initially at least ten times more massive than is now observed.

We have recently carried out hydrodynamical and N-body simulations to explore the formation and dynamical evolution of multiple population clusters formed out of AGB star ejecta (D'Ercole et al. 2008). Our simulations show that the gas lost by FG AGB stars collects in a cooling flow in the cluster core, where most SG stars are formed. We have further demonstrated a dynamical mechanism whereby, after the centrally concentrated SG stars have formed, the cluster's response to early mass loss (of intracluster gas and/or supernova ejecta) leads to the escape of a substantial fraction of FG stars. During the subsequent long-term evolution, the SG and FG populations mix by two-body relaxation, plausibly leading to the multiple-population clusters observed today.

We now explore the implications for the growth of a pre-existing seed black hole of the physical conditions in the central regions of the cluster during the SG formation phase.

3. GROWTH OF A SEED BLACK HOLE

In the hydrodynamical simulations presented in D'Ercole et al. (2008), we assumed that the cluster FG stars followed a King (1962) density profile

$$\rho = \rho_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3/2} \quad (1)$$

out to a truncation radius R_t , with stellar masses distributed in the range $0.1 < m/m_{\odot} < 100$ according to a “Kroupa” initial mass function (Kroupa et al. 1993). We adopted a concentration $c = \log(R_t/r_c) = 1.5$ and followed the evolution of the AGB ejecta in clusters having different values of the total FG mass M and truncation radius R_t .

Figure 1 shows the time evolution of the AGB ejecta density and sound speed within 0.1 pc of the cluster center during the SG formation phase, for four clusters spanning broad ranges in initial mass and tidal radius. In all cases, if the cluster already hosts a seed black hole with mass $M_{BH} \sim 10^2 M_{\odot}$ —the result of one of the “prompt” low-mass IMBH formation mechanisms discussed previously, operating in the FG population—the gas conditions shown in Figure 1 will lead to accretion. The Bondi accretion rate onto a black hole of mass M_{BH} is

$$\dot{M} \simeq 3 \times 10^{-4} \left(\frac{M_{BH}}{100 M_{\odot}} \right)^2 \left(\frac{\rho}{10^{-18} \text{ g cm}^{-3}} \right) \times \left(\frac{3 \text{ km s}^{-1}}{c_s} \right)^3 M_{\odot} \text{ yr}^{-1} \quad (2)$$

where the density ρ and the sound speed c_s have been normalized to the typical values found in our simulations and shown in Figure 1. For the physical conditions in our four simulations, the Bondi accretion rate is $\sim 10^{-4} -$

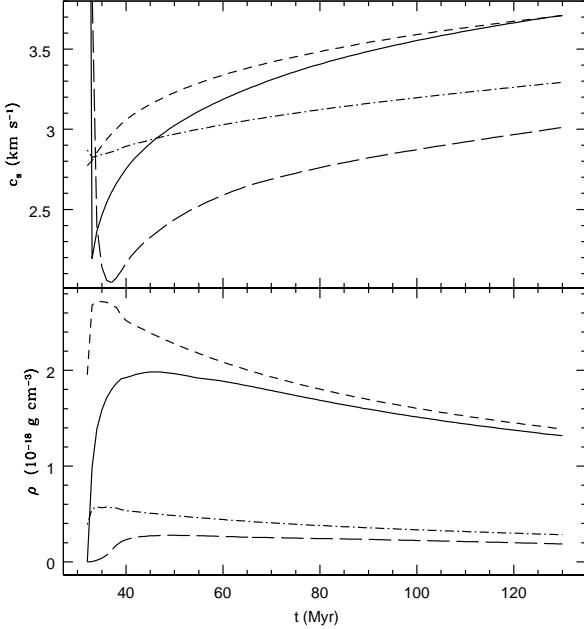


FIG. 1.— Time evolution of the AGB ejecta density (lower panel) and sound speed (upper panel) within 0.1 pc of the cluster center during the SG formation phase for a cluster with FG total mass M and tidal radius R_t equal to $(10^7 M_\odot, 200 \text{ pc})$ (solid line), $(10^7 M_\odot, 40 \text{ pc})$ (dashed line), $(10^6 M_\odot, 90 \text{ pc})$ (long-dashed line), $(10^6 M_\odot, 18 \text{ pc})$ (dot-dashed line).

$10^{-3} M_\odot/\text{yr}$, much larger than the Eddington rate, $\sim 3 \times 10^{-9} (M_{BH}/M_\odot)/\eta M_\odot/\text{yr}$ (Krolik 1999), where η is the radiative efficiency, to be discussed further below. The black hole will therefore accrete gas at the Eddington rate.

Under these circumstances, the black hole mass will grow on a Salpeter time scale

$$T_S \simeq 3.9 \times 10^8 \eta L_E / L \text{ yr}, \quad (3)$$

where $L_E \sim 1.45 \times 10^{38} M_{BH}/M_\odot \text{ erg/s}$ is the Eddington luminosity and a value of the mass per electron $\mu_e \sim 1.15$ has been adopted (see e.g. Krolik 1999). The value of η is uncertain and depends on the properties of the accretion disk and on the spin of the accreting black hole. Here we adopt $\eta \sim 0.05 - 0.1$, a range commonly adopted in studies of black hole growth in galactic nuclei. We note that values of η larger than 0.1, appropriate for rapidly rotating black holes, would reduce the growth of the IMBH, while much smaller values ($\eta \ll 1$) typical of thick accretion disks would significantly increase the IMBH growth rate. For accretion at the Eddington rate with $\eta \sim 0.05 - 0.1$, $T_S \sim 20 - 40 \text{ Myr}$.

The duration of the SG star formation episode in the models of D'Ercole et al. (2008) is $\Delta T \approx 10^2 \text{ Myr}$. This time scale is constrained by spectroscopic observations showing little variation in the total CNO of FG and SG stars, implying that only AGB progenitors with $M > 4 - 5 M_\odot$ must have contributed gas to the SG formation process. Thus, if the seed black hole accretes at close to the Eddington rate during this time, its mass will grow by a factor of $\sim 10 - 100$, leading, by the end of the SG formation phase, to a final black hole mass of

$$M_{BH} \sim 10^3 - 10^4 M_\odot.$$

4. DISCUSSION

Several aspects of the scenario just presented merit further discussion and exploration.

We consider first the effect on the cooling flow of the energy radiated by the accreting black hole. To address this issue we follow the analysis of black hole outflow presented by King (2003, 2005), in which it is shown that the wind produced by the black hole sweeps up the surrounding gas into an expanding shell. Because of effective energy losses due to inverse Compton scattering, the shell expands in the momentum-conserving regime. Under these conditions (see King 2003, 2005), in order for the momentum flux from a black hole accreting at the Eddington rate to overcome gravity and expel the shell from the cluster, the black hole mass must be larger than

$$M_{BH,crit} = \frac{f_g \kappa \sigma^4}{\pi G^2}. \quad (4)$$

Here, κ is the electron scattering opacity, f_g is the fraction of the total cluster mass in the form of gas, and it has been assumed that the gas is embedded in an isothermal system with velocity dispersion σ .

Assuming $\sigma \gtrsim 20 \text{ km/s}$ (the smallest value for which the AGB ejecta can be retained) and $f_g \approx 0.05$ (D'Ercole et al. 2008), we find $M_{BH,crit} \gtrsim 10^4 M_\odot$, much larger than the assumed mass of our initial seed black hole. Thus feedback from the accreting black hole is *not* sufficient to alter significantly the global dynamics of the cooling flow or the SG star formation process.

On the other hand, the effects of feedback may significantly alter the local gas dynamics in the vicinity of the black hole. For example, recent detailed 2-D hydrodynamical models of accretion onto a $100 M_\odot$ seed black hole in a dense protogalactic cloud (Milosavljevic et al. 2009) show intermittent accretion, reducing the net accretion rate to about 1/3 of Eddington. Such a reduction in the mean accretion rate in our case would reduce the growth of the seed black hole to a factor $\sim 2 - 5$ for the range of η values adopted in §3.

We note here that during the accretion phase the black hole will be very luminous and might be observed as a (possibly intermittent) ultraluminous X-ray source (ULX). We caution however that, before linking this scenario to the ULXs observed in nearby young massive clusters (see e.g. Portegies Zwart et al. 2010), one must first verify whether these clusters (1) meet the conditions to form a seed black hole, (2) are sufficiently massive and (3) have the structural properties required for SG star formation.

A second important issue is the possible relation between the IMBH mass and the current structural properties of the parent cluster.

Any correlation between the mass of the seed black hole and the early properties of the cluster should be preserved during the Eddington growth phase, provided that the duration ΔT of the SG star formation episode is approximately independent of the cluster environment. The mass of the seed black hole depends on its formation mechanism. If it is the result of stellar evolution in a massive Pop. III progenitor, a roughly universal

mass seems the most likely result (see e.g. Madau & Rees 2001). Early dynamical simulations of the runaway merger scenario suggested that the mass of the runaway should scale with the mass of the cluster (or the cluster core) in which it forms (Gürkan et al. 2004, Portegies Zwart et al. 2004). However, as mentioned in §1, strong stellar winds may well limit the actual mass attained, possibly to as little as a few hundred solar masses, again largely independent of the initial cluster mass.

For the black hole growth phase to occur, the cluster must *initially* have been massive and/or compact enough to retain the AGB ejecta that subsequently flowed into the cluster core and formed the SG population. As discussed in D'Ercole et al. (2008), multiple population clusters must have undergone an early phase of strong FG mass loss and structural evolution; it is therefore

not straightforward to connect the initial properties of a cluster during the growth of the seed black hole with the current properties of the cluster hosting an IMBH. However, given the loss of most of the FG population and the possible near-universality of the seed black hole mass, the most likely outcome of the scenario described here seems to be one in which the present IMBH mass has only a weak dependence on current cluster properties.

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